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1 **METALLIC COATINGS, AND METHODS OF FORMING**

2 **HARDENED SURFACES**

3
4 **CONTRACTUAL ORIGIN OF THE INVENTION**

5 This invention was made with United States Government support under Contract
6 No. DE-AC07-99ID13727 awarded by the United States Department of Energy. The
7 United States Government has certain rights in the invention.

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10 **TECHNICAL FIELD**

11 The invention pertains to metallic coatings and methods of forming metallic
12 coatings.

13
14 **BACKGROUND OF THE INVENTION**

15 Steel is a metallic alloy which can have exceptional strength characteristics, and
16 which is accordingly commonly utilized in structures where strength is required or
17 advantageous. Steel can be utilized, for example, in the skeletal supports of building
18 structures, tools, engine components, and protective shielding of modern armaments.

19 The composition of steel varies depending on the application of the alloy. For
20 purposes of interpreting this disclosure and the claims that follow, "steel" is defined as
21 any iron-based alloy in which no other single element (besides iron) is present in excess
22 of 30 weight percent, and for which the iron content amounts to at least 55 weight

percent, and carbon is limited to a maximum of 2 weight percent. In addition to iron, steel alloys can incorporate, for example, manganese, nickel, chromium, molybdenum, and/or vanadium. Steel alloys can also incorporate carbon, silicon, phosphorus and/or sulfur. However, phosphorus, carbon, sulfur and silicon can be detrimental to overall steel quality if present in quantities greater than a few percent. Accordingly, steel typically contains small amounts of phosphorus, carbon, sulfur and silicon.

Steel comprises regular arrangements of atoms, with the periodic stacking arrangements forming 3-dimensional lattices which define the internal structure of the steel. The internal structure (sometimes called "microstructure") of conventional steel alloys is always metallic and polycrystalline (consisting of many crystalline grains).

Steel is typically formed by cooling a molten alloy. The rate of cooling will determine whether the alloy cools to form an internal structure that predominately comprises crystalline grains, or, in rare cases, a structure which is predominately amorphous (a so-called metallic glass). Generally, it is found that if the cooling proceeds slowly (i.e., at a rate less than about 10^4 K/s), large grain sizes occur, while if the cooling proceeds rapidly (i.e., at a rate greater than or equal to about 10^4 K/s) microcrystalline internal grain structures are formed, or, in specific rare cases amorphous metallic glasses are formed. The particular composition of the molten alloy generally determines whether the alloy solidifies to form microcrystalline grain structures or an amorphous glass when the alloy is cooled rapidly. Also, it is noted that particular alloy compositions (not iron based) have recently been discovered which can lead to microscopic grain formation, or

1 metallic glass formation, at relatively low cooling rates (cooling rates on the order of 10
2 K/s).

3 Both microcrystalline grain internal structures and metallic glass internal
4 structures can have properties which are desirable in particular applications for steel. In
5 some applications, the amorphous character of metallic glass can provide desired
6 properties. For instance, some glasses can have exceptionally high strength and hardness.
7 In other applications, the particular properties of microcrystalline grain structures are
8 preferred. Frequently, if the properties of a grain structure are preferred, such properties
9 will be improved by decreasing the grain size. For instance, desired properties of
10 microcrystalline grains (i.e., grains having a size on the order of 10^{-6} meters) can
11 frequently be improved by reducing the grain size to that of nanocrystalline grains (i.e.,
12 grains having a size on the order of 10^{-9} meters). It is generally more problematic to form
13 grains of nanocrystalline grain size than it is to form grains of microcrystalline grain size.
14 Accordingly, it is desirable to develop improved methods for forming nanocrystalline
15 grain size steel materials. Further, as it is frequently desired to have metallic glass
16 structures, it is desirable to develop methods of forming metallic glasses.

17 18 **SUMMARY OF THE INVENTION**

19 In one aspect, the invention encompasses a method of forming a metallic coating.
20 A metallic glass coating is formed over a metallic substrate. After formation of the
21 coating, at least a portion of the metallic glass can be converted into a crystalline material
22 having a nanocrystalline grain size.

1 In another aspect, the invention encompasses metallic coatings comprising
2 metallic glass.

3 In yet another aspect, the invention encompasses metallic coatings comprising
4 crystalline metallic material, with at least some of the crystalline metallic material having
5 a nanocrystalline grain size.

6
7 **BRIEF DESCRIPTION OF THE DRAWINGS**

8 Preferred embodiments of the invention are described below with reference to the
9 following accompanying drawings.

10 Fig. 1 is a block-diagram flowchart view of a method encompassed by the present
11 invention.

12 Fig. 2 is a diagrammatic perspective view of a barrel being treated according to a
13 method of the present invention.

14 Fig. 3 is a fragmentary, diagrammatic, cross-sectional view of a metallic material
15 substrate at a preliminary step of a treatment process encompassed by the present
16 invention.

17 Fig. 4 is a view of the Fig. 3 fragment shown at a processing step subsequent to
18 that of Fig. 3.

19 Fig. 5 is a view of the Fig. 3 fragment shown at a processing step subsequent to
20 that of Fig. 4.

21 Fig. 6 is a view of the Fig. 3 fragment shown at a processing step subsequent to
22 that of Fig. 5.

1 Fig. 7 is an optical micrograph of a metallic glass ribbon formed in accordance
2 with methodology of the present invention, and formed from a composition comprising
3 $\text{Fe}_{63}\text{Cr}_8\text{Mo}_2\text{B}_{17}\text{C}_5\text{Si}_1\text{Al}_4$.

4 Fig. 8 is a scanning electron microscope micrograph of a cross section of a gas
5 atomized powder particle formed in accordance with the present invention, and formed
6 from a composition comprising $\text{Fe}_{63}\text{Cr}_8\text{Mo}_2\text{B}_{17}\text{C}_5\text{Si}_1\text{Al}_4$.

7 Fig. 9 is a graph illustrating the results of a differential thermal analysis scan of a
8 ribbon produced in accordance with the present invention. The ribbon was produced
9 from a composition comprising $\text{Fe}_{63}\text{Cr}_8\text{Mo}_2\text{B}_{17}\text{C}_5\text{Si}_1\text{Al}_4$. An exothermic glass to
10 crystallization transition occurs at 550°C , and an endothermic solid to liquid melting
11 transition occurs at $1,150^\circ\text{C}$.

12 Fig. 10 is a TEM micrograph of a steel alloy produced in accordance with the
13 methodology of the present invention, and comprising a composition
14 $\text{Fe}_{63}\text{Cr}_8\text{Mo}_2\text{B}_{17}\text{C}_5\text{Si}_1\text{Al}_4$, which has been heat treated for 650°C for one hour. A nanoscale
15 nanocomposite microstructure is visible, with phase sizes from 1 to 75 nanometers.

16 Fig. 11 illustrates Vickers hardness for different metallic alloys. Specifically, the
17 figure compares DAR1 ($\text{Fe}_{63}\text{Cr}_8\text{Mo}_2\text{B}_{17}\text{C}_5\text{Si}_1\text{Al}_4$) with DAR20
18 ($\text{Fe}_{64}\text{Ti}_3\text{Cr}_5\text{Mo}_2\text{B}_{16}\text{C}_5\text{Si}_1\text{Al}_2\text{La}_2$). The hardness is compared as a function of heat treatment
19 temperature.

20 Fig. 12 shows examples of Vickers hardness tests using a diamond pyramid
21 indenter. Specifically, a top portion of the figure shows the test relative to gas atomized

1 powder particles, and a lower portion shows the test utilized for a melt-spun ribbon. The
2 tested composition was $\text{Fe}_{63}\text{Cr}_8\text{Mo}_2\text{B}_{17}\text{C}_5\text{Si}_1\text{Al}_4$.

3 Fig. 13 is an optical micrograph of a steel composition which has been plasma
4 sprayed onto a stainless steel substrate. The plasma-sprayed steel composition comprises
5 $\text{Fe}_{63}\text{Cr}_8\text{Mo}_2\text{B}_{17}\text{C}_5\text{Si}_1\text{Al}_4$. The top portion of Fig. 9(a) is a cross-sectional view of the
6 sprayed material, and the lower portion (b) shows a top surface of the coated material.

7 Fig. 14 illustrates an x-ray diffraction scan of a plasma-sprayed deposit having a
8 free surface. The plasma-sprayed composition was $\text{Fe}_{63}\text{Cr}_8\text{Mo}_2\text{B}_{17}\text{C}_5\text{Si}_1\text{Al}_4$.

9 Fig. 15 shows an x-ray diffraction scan of the plasma-sprayed composition of Fig.
10 14, and illustrates the structure at the substrate surface.

11 Fig. 16 illustrates a graph showing coefficient of friction versus the number of
12 turns for Pin On Disk testing of a spray coating. The tested coating was
13 $\text{Fe}_{63}\text{Cr}_8\text{Mo}_2\text{B}_{17}\text{C}_5\text{Si}_1\text{Al}_4$. It is noted that while the initial friction was low, Si_3N_4
14 deposition and buildup caused the friction to increase. (The sliding friction of Si_3N_4 on
15 itself is 0.8).

16 Fig. 17 is a profile curve of a "wear-groove" on an as-sprayed steel substrate after
17 2,000 cycles of Pin On Disk testing. As shown, instead of a groove developing on the
18 steel substrate, the Si_3N_4 wore and deposited material onto the substrate. The tested
19 composition was $\text{Fe}_{63}\text{Cr}_8\text{Mo}_2\text{B}_{17}\text{C}_5\text{Si}_1\text{Al}_4$.

20 Fig. 18 is an optical micrograph of an as-spun ribbon of $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{81}\text{B}_{17}\text{W}_2$. The
21 alloy exhibits high ductility, and can be bent severely without fracture.

Fig. 19 illustrates data obtained from differential thermal analysis of $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{75}\text{B}_{17}\text{Si}_4\text{Al}_4$ (top graph) and $\text{Fe}_{63}\text{Cr}_8\text{Mo}_2\text{B}_{17}\text{C}_5\text{Si}_1\text{Al}_4$ (lower graph). The graph curves show glass to crystalline transitions and melting temperatures for the tested alloys.

Fig. 20 shows peak crystallization temperatures measured by differential thermal analysis for a variety of alloys. Specifically, Fig. 20 shows the alloy $\text{Fe}_{63}\text{Cr}_8\text{Mo}_2\text{B}_{17}\text{C}_5\text{Si}_1\text{Al}_4$ as 1, $(\text{Fe}_{0.85}\text{Cr}_{0.15})_{83}\text{B}_{17}$ as 2, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{83}\text{B}_{17}$ as 3, $(\text{Fe}_{0.75}\text{Cr}_{0.25})_{83}\text{B}_{17}$ as 4, $(\text{Fe}_{0.8}\text{Mo}_{0.2})_{83}\text{B}_{17}$ as 5, $(\text{Fe}_{0.6}\text{Co}_{0.2}\text{Cr}_{0.2})_{83}\text{B}_{17}$ as 6, $(\text{Fe}_{0.8}\text{Cr}_{0.15}\text{Mo}_{0.05})_{83}\text{B}_{17}$ as 7, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{79}\text{B}_{17}\text{C}_4$ as 8, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{79}\text{B}_{17}\text{Si}_4$ as 9, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{79}\text{B}_{17}\text{Al}_4$ as 10, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{75}\text{B}_{17}\text{Al}_4\text{C}_4$ as 11, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{75}\text{B}_{17}\text{Si}_4\text{C}_4$ as 12, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{75}\text{B}_{17}\text{Si}_4\text{Al}_4$ as 13, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{71}\text{B}_{17}\text{Si}_4\text{C}_4\text{Al}_4$ as 14, $(\text{Fe}_{0.7}\text{Co}_{0.1}\text{Cr}_{0.2})_{83}\text{B}_{17}$ as 15, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{76}\text{B}_{17}\text{Al}_7$ as 16, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{79}\text{B}_{17}\text{W}_2\text{C}_2$ as 17, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{81}\text{B}_{17}\text{W}_2$ as 18 and $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{80}\text{B}_{20}$ as 19.

Fig. 21 illustrates crystallization enthalpies measured by differential scanning calorimetry for various alloys encompassed by the present invention. Specifically, Fig. 21 shows the alloy $\text{Fe}_{63}\text{Cr}_8\text{Mo}_2\text{B}_{17}\text{C}_5\text{Si}_1\text{Al}_4$ as 1, $(\text{Fe}_{0.85}\text{Cr}_{0.15})_{83}\text{B}_{17}$ as 2, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{83}\text{B}_{17}$ as 3, $(\text{Fe}_{0.75}\text{Cr}_{0.25})_{83}\text{B}_{17}$ as 4, $(\text{Fe}_{0.8}\text{Mo}_{0.2})_{83}\text{B}_{17}$ as 5, $(\text{Fe}_{0.6}\text{Co}_{0.2}\text{Cr}_{0.2})_{83}\text{B}_{17}$ as 6, $(\text{Fe}_{0.8}\text{Cr}_{0.15}\text{Mo}_{0.05})_{83}\text{B}_{17}$ as 7, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{79}\text{B}_{17}\text{C}_4$ as 8, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{79}\text{B}_{17}\text{Si}_4$ as 9, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{79}\text{B}_{17}\text{Al}_4$ as 10, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{75}\text{B}_{17}\text{Al}_4\text{C}_4$ as 11, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{75}\text{B}_{17}\text{Si}_4\text{C}_4$ as 12, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{75}\text{B}_{17}\text{Si}_4\text{Al}_4$ as 13, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{71}\text{B}_{17}\text{Si}_4\text{C}_4\text{Al}_4$ as 14, $(\text{Fe}_{0.7}\text{Co}_{0.1}\text{Cr}_{0.2})_{83}\text{B}_{17}$ as 15, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{76}\text{B}_{17}\text{Al}_7$ as 16, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{79}\text{B}_{17}\text{W}_2\text{C}_2$ as 17, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{81}\text{B}_{17}\text{W}_2$ as 18 and $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{80}\text{B}_{20}$ as 19.

1 Fig. 22 illustrates a graph of transformation rates of glass to crystallization
2 transformation for various alloys encompassed by the present invention. Specifically,
3 Fig. 22 shows the alloy $\text{Fe}_{63}\text{Cr}_8\text{Mo}_2\text{B}_{17}\text{C}_5\text{Si}_1\text{Al}_4$ as 1, $(\text{Fe}_{0.85}\text{Cr}_{0.15})_{83}\text{B}_{17}$ as 2,
4 $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{83}\text{B}_{17}$ as 3, $(\text{Fe}_{0.75}\text{Cr}_{0.25})_{83}\text{B}_{17}$ as 4, $(\text{Fe}_{0.8}\text{Mo}_{0.2})_{83}\text{B}_{17}$ as 5, $(\text{Fe}_{0.6}\text{Co}_{0.2}\text{Cr}_{0.2})_{83}\text{B}_{17}$ as
5 6, $(\text{Fe}_{0.8}\text{Cr}_{0.15}\text{Mo}_{0.05})_{83}\text{B}_{17}$ as 7, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{79}\text{B}_{17}\text{C}_4$ as 8, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{79}\text{B}_{17}\text{Si}_4$ as 9,
6 $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{79}\text{B}_{17}\text{Al}_4$ as 10, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{75}\text{B}_{17}\text{Al}_4\text{C}_4$ as 11, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{75}\text{B}_{17}\text{Si}_4\text{C}_4$ as 12,
7 $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{75}\text{B}_{17}\text{Si}_4\text{Al}_4$ as 13, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{71}\text{B}_{17}\text{Si}_4\text{C}_4\text{Al}_4$ as 14, $(\text{Fe}_{0.7}\text{Co}_{0.1}\text{Cr}_{0.2})_{83}\text{B}_{17}$ as 15,
8 $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{76}\text{B}_{17}\text{Al}_7$ as 16, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{79}\text{B}_{17}\text{W}_2\text{C}_2$ as 17, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{81}\text{B}_{17}\text{W}_2$ as 18 and
9 $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{80}\text{B}_{20}$ as 19.

10 Fig. 23 illustrates peak melting temperatures measured by differential thermal
11 analysis for various alloys encompassed by the present invention. Specifically, Fig. 23
12 shows the alloy $\text{Fe}_{63}\text{Cr}_8\text{Mo}_2\text{B}_{17}\text{C}_5\text{Si}_1\text{Al}_4$ as 1, $(\text{Fe}_{0.85}\text{Cr}_{0.15})_{83}\text{B}_{17}$ as 2, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{83}\text{B}_{17}$ as 3,
13 $(\text{Fe}_{0.75}\text{Cr}_{0.25})_{83}\text{B}_{17}$ as 4, $(\text{Fe}_{0.8}\text{Mo}_{0.2})_{83}\text{B}_{17}$ as 5, $(\text{Fe}_{0.6}\text{Co}_{0.2}\text{Cr}_{0.2})_{83}\text{B}_{17}$ as 6,
14 $(\text{Fe}_{0.8}\text{Cr}_{0.15}\text{Mo}_{0.05})_{83}\text{B}_{17}$ as 7, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{79}\text{B}_{17}\text{C}_4$ as 8, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{79}\text{B}_{17}\text{Si}_4$ as 9,
15 $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{79}\text{B}_{17}\text{Al}_4$ as 10, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{75}\text{B}_{17}\text{Al}_4\text{C}_4$ as 11, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{75}\text{B}_{17}\text{Si}_4\text{C}_4$ as 12,
16 $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{75}\text{B}_{17}\text{Si}_4\text{Al}_4$ as 13, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{71}\text{B}_{17}\text{Si}_4\text{C}_4\text{Al}_4$ as 14, $(\text{Fe}_{0.7}\text{Co}_{0.1}\text{Cr}_{0.2})_{83}\text{B}_{17}$ as 15,
17 $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{76}\text{B}_{17}\text{Al}_7$ as 16, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{79}\text{B}_{17}\text{W}_2\text{C}_2$ as 17, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{81}\text{B}_{17}\text{W}_2$ as 18 and
18 $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{80}\text{B}_{20}$ as 19.

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1 **DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS**

2 This disclosure of the invention is submitted in furtherance of the constitutional
3 purposes of the U.S. Patent Laws "to promote the progress of science and useful arts"
4 (Article 1, Section 8).

5 The invention encompasses methodology for forming steel materials having
6 nanocrystalline scale composite microstructures, methods of utilizing such steel
7 materials, and also encompasses the steel material compositions. A process encompassed
8 by the present invention is described generally with reference to the block diagram of Fig.

9 1. At an initial step (A) a molten alloy is formed. Such alloy comprises a steel
10 composition. An exemplary alloy comprises at least 50% Fe and at least one element
11 selected from the group consisting of Ti, Zr, Hf, V, Nb, Ta, Cr, Mo, W, Al, La, Ce, Pr,
12 Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu; and at least one element selected from
13 the group consisting of B, C, N, O, P and S. In particular aspects of the present
14 invention, the alloy will be a magnetic alloy with ultrafine crystal grains having a
15 composition represented by the formula: $\text{Fe}(100-x-y)\text{M}(x)\text{B}(y)$ (atomic percent) wherein
16 M represents at least one element selected from Ti, Zr, Hf, V, Nb, Mo, Ta, Cr, W and
17 Mn, wherein $15 \geq x \geq 4$, wherein $25 \geq y \geq 2$, and wherein $35 \geq (x+y) \geq 7$. Also, at least 50% of
18 the alloy structure is preferably occupied by crystal grains having an average size of
19 1000\AA or less, with the crystal grains being based on a bcc structure. The alloy can
20 further contain X (Si, Ge, P, Ga, etc.) and/or T (Au, Co, Ni, etc.).

21 Alloys of the present invention preferably comprise fewer than 11 elements, and
22 can more preferably comprise fewer than seven elements. Additionally, the alloys can

comprise fewer than five elements. An advantage in having fewer elements in the compositions is that it can be easier to reproduce a material if fewer components are utilized in forming the material. Generally, alloys of the present invention have from four to six elements in their compositions. Among such elements are iron; chromium, which can be included for corrosion resistance; boron and/or phosphorus which can be included to generate a particular glass transition temperature; and one or both of molybdenum and tungsten which can be included for hardness.

Exemplary alloys which can be utilized in methodology of the present invention are: $(\text{Fe}_{0.85}\text{Cr}_{0.15})_{83}\text{B}_{17}$, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{83}\text{B}_{17}$, $(\text{Fe}_{0.75}\text{Cr}_{0.25})_{83}\text{B}_{17}$, $(\text{Fe}_{0.8}\text{Mo}_{0.2})_{83}\text{B}_{17}$, $(\text{Fe}_{0.6}\text{Co}_{0.2}\text{Cr}_{0.2})_{83}\text{B}_{17}$, $(\text{Fe}_{0.8}\text{Cr}_{0.15}\text{Mo}_{0.05})_{83}\text{B}_{17}$, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{79}\text{B}_{17}\text{C}_4$, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{79}\text{B}_{17}\text{Si}_4$, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{79}\text{B}_{17}\text{Al}_4$, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{75}\text{B}_{17}\text{Al}_4\text{C}_4$, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{75}\text{B}_{17}\text{Si}_4\text{C}_4$, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{75}\text{B}_{17}\text{Si}_4\text{Al}_4$, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{71}\text{B}_{17}\text{Si}_4\text{C}_4\text{Al}_4$, $(\text{Fe}_{0.7}\text{Co}_{0.1}\text{Cr}_{0.2})_{83}\text{B}_{17}$, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{76}\text{B}_{17}\text{Al}_7$, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{79}\text{B}_{17}\text{W}_2\text{C}_2$, $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{81}\text{B}_{17}\text{W}_2$, and $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{80}\text{B}_{20}$.

The alloy of step (A) can be formed by, for example, melting a composition under an argon atmosphere.

At step (B) of Fig. 1, the alloy is cooled to form a metallic glass. Such cooling typically comprises a rate of at least about 10^4 K/s, with the rate varying depending on the particular composition of the molten alloy. The cooling can be accomplished by a number of different processes, including, for example, melt-spinning, gas atomization, centrifugal atomization, water atomization and splat quenching. The powder can be consolidated by, for example, HIPping, hot pressing, hot extrusion, powder rolling, powder forging and dynamic compaction. In an exemplary method, the cooling of step

1 (B) is accomplished by centrifugal atomization. Preferably, the melt stream leaves a
2 centrifugal cup and is hit by high pressure helium gas to facilitate fast cooling (greater
3 than 10^5 K/s.) The helium gas can be collected, purified and reused. The speed of the
4 rotating centrifugal cup is preferably about 40,000 RPM, and such speed can be adjusted
5 to produce a fine powder with about a 25 micrometer mean size.

6 Referring to step (C) of Fig. 1, the metallic glass of step (B) is devitrified to form
7 a crystalline steel material having a nanocrystalline grain size. Such devitrification can
8 be accomplished by heating the metallic glass to a temperature of from about 600°C to
9 less than the melting temperature of the alloy. Such heating enables a solid state phase
10 change wherein the amorphous phase of the metallic glass is converted to one or more
11 crystalline solid phases. The solid state devitrification of the amorphous precursor from
12 step (B) enables uniform nucleation to occur throughout the metallic glass to form
13 nanocrystalline grains within the glass. The metal matrix microstructure formed via the
14 devitrification can comprise a steel matrix (iron with dissolved interstitials), with an
15 intimate mixture of ceramic precipitates (transition metal carbides, borides, silicides,
16 etc.). The nanocrystalline scale metal matrix composite grain structure can enable a
17 combination of mechanical properties which are improved compared to the properties
18 which would exist with larger grain sizes or with the metallic glass. Such improved
19 mechanical properties can include, for example, high strength, and high hardness coupled
20 with significant ductility.

21 The particular temperature employed for devitrifying the metal glass can be varied
22 depending on the particular alloy utilized in the glass, and a particular time of application.

Post treatment of the devitrified metallic material from step (C) can include a surface treatment utilized to transform only the surface of the material to a metallic glass. Exemplary surface treatment techniques are high and low pressure plasma spraying, high velocity oxyfuel spraying, and spray forming. The plasma spraying can be accomplished with a plasma spray system. The post treatment can offer improvements in, for example, corrosion resistance and lowering the coefficient of friction of a steel material. Accordingly, it can be advantageous to treat at least the surface of a crystalline steel material to convert such surface to a metallic glass. It is noted that a metallic glass coating can also offer advantages over existing coatings such as, for example, chrome, nickel and tin plating in that the metallic glass coating can be cheaper and can give a better metallurgical bond between the surface and the base metal.

Referring to Fig. 2, a specific embodiment application of the present invention is illustrated. Specifically, Fig. 2 illustrates a metallic barrel 50 being sprayed with a molten metal material 52. Molten metal material 52 is sprayed from a spraying device 54, and can comprise, for example, one or more of the above-described exemplary alloys of the present invention. The molten metal can be formed by melting an alloy composition under an argon atmosphere and subsequently centrifugally atomizing the alloy composition. As the melt stream leaves a centrifugal cup, it can be hit by a high pressure helium gas to form a fine powder of solidified metallic alloy material with such fine powder having about a 25 micrometer mean size. The fine powder can be fed into a plasma (high or low pressure) system wherein it is converted to a liquid spray which is sprayed on the inside and outside of metallic drum 50. In particular applications, drum

1 can alternatively comprise a powder material heated to a sufficient temperature to bond
2 with the metal of layer 100.

3 Material 102 deposits on substrate 100 to form a layer 106. Material 102 also
4 heats an exposed surface of material 100 to form a heat-treated portion 108 of material
5 100. If material 100 comprises a metallic glass, heat-treated portion 108 can comprise a
6 devitrified material. Specifically, if layer 106 is formed at a temperature which heats a
7 surface of layer 100 to greater than 600°C, such heating can devitrify a portion of
8 material 100 exposed to such temperatures. In particular applications, temperatures
9 greater than 600°C can permeate entirely through substrate 100 to heat-treat an entire
10 thickness of material 100. Spray nozzle 104 is preferably resistant to the temperature and
11 composition of material 102.

12 Referring to Fig. 5, substrate 100 is illustrated after layer 106 has been formed
13 across an entire surface of substrate 100. Heat-treated portion 108 also extends across an
14 entire surface of substrate 100. In particular embodiments, layer 106 can be formed as a
15 metallic glass.

16 Referring to Fig. 6, subsequent treatments of the type illustrated in Fig. 4 can be
17 utilized to form multiple heat-treated layers 120 and an exposed outer surface layer 124.
18 Note that one of the lower heat-treated layers 120 is previous layer 106. The subsequent
19 formation of another metallic glass layer over layer 106 has heat-treated the entire layer
20 106. In particular embodiments wherein layer 106 comprises a metallic glass, such heat
21 treatment can devitrify layer 106. Accordingly, heat treated layers 120 can comprise
22 devitrified metal layers. In alternative methods of the present invention, each of the

for grain growth before impingement between neighboring grains and accordingly nanoscale nanocomposite microstructures are formed. The individual phase sizes can vary from 1 to 75 nanometers, which is finer than conventional steels produced by conventional casting or even when rapidly solidified. When the microstructure is reduced to the nanoscale level, a high percentage of the atoms of the material (about 30%) can be associated with grain boundaries, and an extremely high density of two-dimensional defect interfaces (such as phase in grain boundaries) reside in the microstructure. The microstructure of a devitrified ribbon showing the nanoscale nanocomposite microstructure is shown in Fig. 10. The nanostructure results in the development of extreme strength and hardness, which are significantly higher than found in conventional steel or other metallic based alloys.

The hardness of glass and devitrified DNC steel has been measured using both nanoindenter and Vickers microhardness testing, and excellent agreement is found between the two methods. Specialized nanoindenter testing using a Berkovich indenter was performed on the as-atomized and heat-treated sieved (10-20 micrometer and 75-100 micrometer) gas atomized particles from a $\text{Fe}_{63}\text{Cr}_8\text{Mo}_2\text{B}_{17}\text{C}_5\text{Si}_1\text{Al}_4$ alloy as a function of depth into the particle. The elastic modulus was found to be as high as 300 GPa, which is approximately 50% higher than a conventional steel (which commonly exhibits elastic moduli from 200 GPa to 220 GPa). This means that bonding strength is increased, which can be of beneficial result since it allows close tolerances to be maintained during application of high elastic loads, and can have additional benefits concerning wear resistance. The hardness was also found to be extremely high at greater than 15 GPa,

TABLE 1
DNC Alloy Compositions

Alloy	Composition
DAR1	$\text{Fe}_{63}\text{Cr}_8\text{Mo}_2\text{B}_{17}\text{C}_5\text{Si}_1\text{Al}_4$
DAR2	$(\text{Fe}_{0.85}\text{Cr}_{0.15})_{83}\text{B}_{17}$
DAR3	$(\text{Fe}_{0.8}\text{Cr}_{0.2})_{83}\text{B}_{17}$
DAR4	$(\text{Fe}_{0.75}\text{Cr}_{0.25})_{83}\text{B}_{17}$
DAR5	$(\text{Fe}_{0.8}\text{Mo}_{0.2})_{83}\text{B}_{17}$
DAR6	$(\text{Fe}_{0.6}\text{Co}_{0.2}\text{Cr}_{0.2})_{83}\text{B}_{17}$
DAR7	$(\text{Fe}_{0.8}\text{Cr}_{0.15}\text{Mo}_{0.05})_{83}\text{B}_{17}$
DAR8	$(\text{Fe}_{0.8}\text{Cr}_{0.2})_{79}\text{B}_{17}\text{C}_4$
DAR9	$(\text{Fe}_{0.8}\text{Cr}_{0.2})_{79}\text{B}_{17}\text{Si}_4$
DAR10	$(\text{Fe}_{0.8}\text{Cr}_{0.2})_{79}\text{B}_{17}\text{Al}_4$
DAR11	$(\text{Fe}_{0.8}\text{Cr}_{0.2})_{75}\text{B}_{17}\text{Al}_4\text{C}_4$
DAR12	$(\text{Fe}_{0.8}\text{Cr}_{0.2})_{75}\text{B}_{17}\text{Si}_4\text{C}_4$
DAR13	$(\text{Fe}_{0.8}\text{Cr}_{0.2})_{75}\text{B}_{17}\text{Si}_4\text{Al}_4$
DAR14	$(\text{Fe}_{0.8}\text{Cr}_{0.2})_{71}\text{B}_{17}\text{Si}_4\text{C}_4\text{Al}_4$
DAR15	$(\text{Fe}_{0.7}\text{Co}_{0.1}\text{Cr}_{0.2})_{83}\text{B}_{17}$
DAR16	$(\text{Fe}_{0.8}\text{Cr}_{0.2})_{76}\text{B}_{17}\text{Al}_7$
DAR17	$(\text{Fe}_{0.8}\text{Cr}_{0.2})_{79}\text{B}_{17}\text{W}_2\text{C}_2$
DAR18	$(\text{Fe}_{0.8}\text{Cr}_{0.2})_{81}\text{B}_{17}\text{W}_2$
DAR19	$(\text{Fe}_{0.8}\text{Cr}_{0.2})_{80}\text{B}_{20}$
DAR20	$\text{Fe}_{64}\text{Ti}_3\text{Cr}_5\text{Mo}_2\text{B}_{16}\text{C}_5\text{Si}_1\text{Al}_2\text{La}_2$

TABLE 2
Example Hardness of Metallic Materials

Material	Hardness
18 Cr-10 Ni austenitic stainless steel	1.5 GPa
0.74 plain carbon steel	4.9 GPa
4340 ultra high strength steel	5.5 GPa
T5 W tool steel	7.5 GPa
90 WC - 10 Co cemented carbide	10.1 GPa
$\text{Fe}_{63}\text{Cr}_8\text{Mo}_2\text{B}_{17}\text{C}_5\text{Si}_1\text{Al}_4$ (DAR1)	15.5 GPa

From the hardness determined for DAR1, the yield strengths for the DNC steel can be estimated to be 725 ksi, which is significantly higher than conventional (150 ksi) or ultra high strength (220 ksi) steels. If the plasticity is fully developed, the yield strength can be estimated to be 1/3 of the hardness. This gives the DNC steel a specific strength of $0.65 \times 10^6 \text{M}$ which makes this material an alternate for Al in lightweight applications. Little hardness difference was found between the large and small heated powders indicating that similar microstructures were obtained independent of powder size. It is noted that the hardness tests described herein were relative to a material DAR1 ($\text{Fe}_{63}\text{Cr}_8\text{Mo}_2\text{B}_{17}\text{C}_5\text{Si}_1\text{Al}_4$) which is not a preferred material of the present invention. Rather, preferred materials of the present invention would have fewer elements, and are listed as DAR2 through DAR 19 in Table 1.

A preferred material of the present invention (specifically DAR20) is compared with DAR1 in Fig. 11. Specifically, Vickers microhardness measurements with a 100 gram load were performed on 75 micrometer to 100 micrometer powder size fractions for

as-atomized alloys, and also as a function of heat treatment temperature. The tested alloys exhibited extreme hardness from 10.1 GPa to 16.0 GPa Vickers hardness. Examples of diamond pyramid indentations on a melt-spun ribbon and gas-atomized powder particle are shown in Fig. 12. While the Rockwell C is the most common hardness measurement for steels, it cannot be used in the present case due to the extreme hardness of the alloys of the present invention (which are off of the Rockwell C scale). Note that a Vickers Hardness number of 9.2 GPa corresponds to a Rockwell C of 68. Referring again to Fig. 11, it is noted that little hardness change occurs in the as-atomized state of alloys of the present invention after subsequent heat treating. This can be significant, as it means that optimum microstructures are obtained directly during solidification and the optimum structures are stable to high temperatures (at least to 850°C, as shown in Fig. 11).

DNC steels contain multiple combinations of elements which result in relatively low melting points (typically around 1,150°C) and low melt viscosities. This can make the DNC steels easy to process from the liquid state, and ideal feedstock materials for forming coatings by thermal deposition methods. Initial low plasma spraying tests have been performed utilizing the atomized 20 to 50 micrometer $\text{Fe}_{63}\text{Cr}_8\text{Mo}_2\text{B}_{17}\text{C}_5\text{Si}_1\text{Al}_4$ steel powder as feed stock. Several uniform DNC steel coatings of 0.1 inch in thickness were deposited onto 4"x4" 301 stainless steel plates (shown in Fig. 13). While typical thermally deposited coatings are only 25 micrometers to 100 micrometers thick, much thicker coatings (up to 2,500 micrometers) were sprayed to illustrate an extreme case (in

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1 other words, thinner coatings are easier to spray, but thicker coatings were sprayed to
2 illustrate operability of a method of the present invention).

3 Metallographic examinations of the coatings indicate that the percent porosity of
4 the initial coatings was at least 3%. X-ray diffraction scans were performed both on the
5 substrate side and free surface side of the coatings, and show that an amorphous structure
6 was obtained through the cross-sectioning of the coatings (specifically, Fig. 14 shows an
7 x-ray structure of a free surface side of the coating, and Fig. 15 shows an x-ray structure
8 of the substrate side of the coating). Differential scanning calorimetry methods verified
9 the formation of the glass structure in the coating which exhibited a high crystallization
10 enthalpy (-110 J/g). This result is surprising due to the supreme thickness of the coating
11 which resulted from successive build-up of continuous layers of deposited powder, and
12 the fact that the substrate was not cooled. Thus, DNC steel coatings represent a class of
13 materials called bulk glasses. Bulk glasses are normally very difficult to produce, but
14 readily form in the DNC alloys by thermal processing methods.

15 The as-sprayed DNC metallic glass coatings can be devitrified into a nanoscale
16 structure by heating above the crystallization temperature. However, due to the unique
17 properties of the metallic glasses, the glass state itself may be useful as a coating.
18 Metallic glasses are essentially super-cooled liquids, and have structures which are very
19 homogeneous. Typically there are few defects, and there can be a complete absence of
20 grains and phase boundaries. Hardness testing was performed on both the as-sprayed
21 (amorphous) and heat-treated (800°C for one hour) nanocrystalline coatings. The
22 Vickers hardness of these coatings was found to be 10.9 GPa and 13.8 GPa for the as-

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1 sprayed and heat-treated coatings, respectively. It is noted that while the amorphous
2 sample is not as hard as the crystalline sample, it is still harder than the hardest tool steel
3 (about 9.3 GPa), or tungsten carbon (WC) cemented carbide cutting tool (about 10.0
4 GPa).

5 Tribology testing experiments were done on the as-sprayed and heat-treated
6 (100°C for one hour) plasma sprayed coatings using ASTM G99 Pin-on-Disk tests. The
7 "pin" was a one-half inch diameter Si_3N_4 ball which was rotated at a test speed of 97
8 RPM, with a test radius of 10.4 mm and with no lubrication. During the test, the
9 coefficients of friction were measured (shown in Fig. 16). The coefficient of static
10 friction for the steel substrate in both the as-sprayed and heat-treated condition was 0.22,
11 which represents a low value. For example, the following coefficients of sliding friction
12 were obtained for specimens sliding over a normalized steel (0.13% C, 3.42% Ni):
13 aluminum (0.6), cartridge brass (0.5), copper (0.8), cast iron (0.4), and normalized steel
14 (on itself 0.8). For conventional steels, the coefficients of static friction for unlubricated
15 surfaces generally vary from 0.8 to 1.0, while lubricated steels have much lower values
16 (typically from 0.1 to 0.25). Thus, the unlubricated DNC steels have coefficients of static
17 friction in the range of lubricated steel surfaces. Accordingly, utilization of DNC steel
18 coatings in place of conventional steel may allow the elimination of lubrication in some
19 applications. Note that the coefficient of sliding friction of the steel substrate could not
20 be measured due to Si_3N_4 deposition from the pin.

21 The profile of the wear surface of the steel showed that the steel experienced no
22 wear during the test (Fig. 17). Instead of the expected wear groove, a raised hill of

1 deposited Si_3N_4 was found on the steel surface. Examination of the silicon nitride ball
2 showed that it experienced a large ball scar as a result of wear. This was surprising due to
3 the hardness of the ball material (15.4 GPa), which is used specifically for these type of
4 tests due to its excessive hardness and wear resistance. Note that Si_3N_4 is currently the
5 hardest pin material available to perform this ASTM test.

6 The $\text{Fe}_{63}\text{Cr}_8\text{Mo}_2\text{B}_{17}\text{C}_5\text{Si}_1\text{Al}_4$ steel utilized in generating the data described above is
7 an exemplary DNC steel. However, it suffers from a disadvantage of having numerous
8 elements included therein, which can make it difficult to produce uniform batches of the
9 material. Accordingly, improved DNC alloys have been developed. Such improved
10 alloys are listed in Table 1 as DAR2 through DAR19. The alloys have been designed to
11 form metallic glasses at low cooling rates, and are further designed to reduce the number
12 of elements utilized in the alloys.

13 Ingots of the 19 alloys listed in Table 1 were melt-spun at 15 m/s with the
14 following melt-spinning parameters: chamber 1/3 atmosphere helium, ejection pressure
15 150 Torr, ejection temperature $1,400^\circ\text{C}$, crucible up to wheel distance 6 mm, and crucible
16 orifice diameter 0.81 mm to 0.84 mm.

17 All of the tested alloys were melt-spun with few problems. Interestingly, many of
18 the preferred alloys (i.e., DAR2 through DAR19) formed uniform continuous ribbons up
19 to 10 meters in length. This may be due to increased glass forming ability and increased
20 ductility of the glass that is produced relative to the less preferred alloy DAR1.
21 Qualitative inspections of the ribbons by bending the ribbons back and forth until fracture
22 indicated that all of the alloys DAR2 through DAR19 have higher ductility than the

DAR1 alloy. In fact, some of the alloys DAR2 through DAR 19 in ribbon-form cannot be broken by bending, and had to be cut. An example of a melt-spun ribbon which exhibits high ductility is shown in Fig. 18, and was formed from the material DAR18 $(\text{Fe}_{0.8}\text{Cr}_{0.2})_{81}\text{B}_{17}\text{W}_2$.

Differential thermal analysis (DTA) and differential thermal calorimetry (DSC) studies were done on each melt-spun ribbon sample in ultra-high purity argon from 30°C to 1,375°C at a heating rate of 10°C/min. A typical DTA scan showing DAR14 $((\text{Fe}_{0.8}\text{Cr}_{0.2})_{75}\text{B}_{17}\text{Si}_4\text{Al}_4)$ compared with DAR1 $(\text{Fe}_{63}\text{Cr}_8\text{Mo}_2\text{B}_{17}\text{C}_5\text{Si}_1\text{Al}_4)$ is illustrated in Fig. 19. From the DTA/DSC studies, the glass to crystalline transformation temperatures, enthalpy of transformation, transformation rate, and melting temperatures could be determined. The results of these studies are shown in Figs. 20-23. As shown, all of the alloys but one (specifically, DAR5 $((\text{Fe}_{0.8}\text{Mo}_{0.2})_{83}\text{B}_{17})$, formed a metallic glass structure when melt-spun at reduced cooling rate. Thus, the alloys are expected to form metallic glass powders when atomized.

Vickers hardness testing using a 100 gram load was done on the cross-sections of the melt-spun ribbons of each alloy in the as-spun and heat-treated (700°C for one hour and 800°C for one hour) conditions. For each sample (60 samples total), 10 Vickers hardness tests on five ribbons were done in order to get a reportable average value. In general, only small variations were found to occur in hardness when the same sample was tested. Summaries of the completed Vickers hardness measurements are shown in Table 4.

TABLE 4

ALLOY	Condition	Hardness (kg/mm ²)	Hardness (GPa)
(Fe _{0.85} Cr _{0.15}) ₈₃ B ₁₇	As-Spun	996	9.77
(Fe _{0.85} Cr _{0.15}) ₈₃ B ₁₇	700°C	835	8.19
(Fe _{0.85} Cr _{0.15}) ₈₃ B ₁₇	800°C	864	8.47
(Fe _{0.8} Cr _{0.2}) ₈₃ B ₁₇	As-Spun	1048	10.28
(Fe _{0.8} Cr _{0.2}) ₈₃ B ₁₇	700°C	935	9.17
(Fe _{0.8} Cr _{0.2}) ₈₃ B ₁₇	800°C	870	8.53
(Fe _{0.75} Cr _{0.25}) ₈₃ B ₁₇	As-Spun	1065	10.45
(Fe _{0.75} Cr _{0.25}) ₈₃ B ₁₇	700°C	1011	9.91
(Fe _{0.75} Cr _{0.25}) ₈₃ B ₁₇	800°C	888	8.71
(Fe _{0.6} Co _{0.2} Cr _{0.2}) ₈₃ B ₁₇	As-Spun	980	9.61
(Fe _{0.6} Co _{0.2} Cr _{0.2}) ₈₃ B ₁₇	700°C	1119	10.97
(Fe _{0.6} Co _{0.2} Cr _{0.2}) ₈₃ B ₁₇	800°C	984	9.65
(Fe _{0.8} Cr _{0.15} Mo _{0.05}) ₈₃ B ₁₇	As-Spun	1062	10.41
(Fe _{0.8} Cr _{0.15} Mo _{0.05}) ₈₃ B ₁₇	700°C	1573	15.43
(Fe _{0.8} Cr _{0.15} Mo _{0.05}) ₈₃ B ₁₇	800°C	900	8.83
(Fe _{0.8} Cr _{0.2}) ₇₉ B ₁₇ C ₄	As-Spun	1103	10.82
(Fe _{0.8} Cr _{0.2}) ₇₉ B ₁₇ C ₄	700°C	1317	12.91
(Fe _{0.8} Cr _{0.2}) ₇₉ B ₁₇ C ₄	800°C	1194	11.71
(Fe _{0.8} Cr _{0.2}) ₇₉ B ₁₇ Si ₄	As-Spun	1096	10.75
(Fe _{0.8} Cr _{0.2}) ₇₉ B ₁₇ Si ₄	700°C	1150	11.28
(Fe _{0.8} Cr _{0.2}) ₇₉ B ₁₇ Si ₄	800°C	885	8.67
(Fe _{0.8} Cr _{0.2}) ₇₉ B ₁₇ Al ₄	As-Spun	1053	10.32
(Fe _{0.8} Cr _{0.2}) ₇₉ B ₁₇ Al ₄	700°C	1119	10.97
(Fe _{0.8} Cr _{0.2}) ₇₉ B ₁₇ Al ₄	800°C	946	9.28
(Fe _{0.8} Cr _{0.2}) ₇₅ B ₁₇ Al ₄ C ₄	As-Spun	1098	10.76

1	$(\text{Fe}_{0.8}\text{Cr}_{0.2})_{75}\text{B}_{17}\text{Al}_4\text{C}_4$	700°C	1380	13.53
2	$(\text{Fe}_{0.8}\text{Cr}_{0.2})_{75}\text{B}_{17}\text{Al}_4\text{C}_4$	800°C	1159	11.37
3	$(\text{Fe}_{0.8}\text{Cr}_{0.2})_{75}\text{B}_{17}\text{Si}_4\text{C}_4$	As-Spun	1184	11.61
4	$(\text{Fe}_{0.8}\text{Cr}_{0.2})_{75}\text{B}_{17}\text{Si}_4\text{C}_4$	700°C	1509	14.80
5	$(\text{Fe}_{0.8}\text{Cr}_{0.2})_{75}\text{B}_{17}\text{Si}_4\text{C}_4$	800°C	1245	12.21
6	$(\text{Fe}_{0.8}\text{Cr}_{0.2})_{75}\text{B}_{17}\text{Si}_4\text{Al}_4$	As-Spun	1063	10.42
7	$(\text{Fe}_{0.8}\text{Cr}_{0.2})_{75}\text{B}_{17}\text{Si}_4\text{Al}_4$	700°C	1266	12.42
8	$(\text{Fe}_{0.8}\text{Cr}_{0.2})_{75}\text{B}_{17}\text{Si}_4\text{Al}_4$	800°C	1055	10.34
9	$(\text{Fe}_{0.8}\text{Cr}_{0.2})_{71}\text{B}_{17}\text{Si}_4\text{C}_4\text{Al}_4$	As-Spun	1093	10.72
10	$(\text{Fe}_{0.8}\text{Cr}_{0.2})_{71}\text{B}_{17}\text{Si}_4\text{C}_4\text{Al}_4$	700°C	1376	13.49
11	$(\text{Fe}_{0.8}\text{Cr}_{0.2})_{71}\text{B}_{17}\text{Si}_4\text{C}_4\text{Al}_4$	800°C	1134	11.12
12	$(\text{Fe}_{0.7}\text{Co}_{0.1}\text{Cr}_{0.2})_{83}\text{B}_{17}$	As-Spun	1042	10.22
13	$(\text{Fe}_{0.7}\text{Co}_{0.1}\text{Cr}_{0.2})_{83}\text{B}_{17}$	700°C	1135	11.13
14	$(\text{Fe}_{0.7}\text{Co}_{0.1}\text{Cr}_{0.2})_{83}\text{B}_{17}$	800°C	885	8.68
15	$(\text{Fe}_{0.8}\text{Cr}_{0.2})_{80}\text{B}_{20}$	As-Spun	1093	10.72
16	$(\text{Fe}_{0.8}\text{Cr}_{0.2})_{80}\text{B}_{20}$	700°C	1045	10.24
17	$(\text{Fe}_{0.8}\text{Cr}_{0.2})_{80}\text{B}_{20}$	800°C	965	9.47
18	$(\text{Fe}_{0.8}\text{Cr}_{0.2})_{76}\text{B}_{17}\text{Al}_7$	As-Spun	1028	10.08
19	$(\text{Fe}_{0.8}\text{Cr}_{0.2})_{76}\text{B}_{17}\text{Al}_7$	700°C	1441	14.13
20	$(\text{Fe}_{0.8}\text{Cr}_{0.2})_{76}\text{B}_{17}\text{Al}_7$	800°C	868	8.51
21	$(\text{Fe}_{0.8}\text{Cr}_{0.2})_{79}\text{B}_{17}\text{W}_2\text{C}_2$	As-Spun	1124	11.02
22	$(\text{Fe}_{0.8}\text{Cr}_{0.2})_{79}\text{B}_{17}\text{W}_2\text{C}_2$	700°C	1653	16.21
23	$(\text{Fe}_{0.8}\text{Cr}_{0.2})_{79}\text{B}_{17}\text{W}_2\text{C}_2$	800°C	1223	11.99
24	$(\text{Fe}_{0.8}\text{Cr}_{0.2})_{81}\text{B}_{17}\text{W}_2$	As-Spun	1052	10.31
25	$(\text{Fe}_{0.8}\text{Cr}_{0.2})_{81}\text{B}_{17}\text{W}_2$	700°C	1565	15.34
26	$(\text{Fe}_{0.8}\text{Cr}_{0.2})_{81}\text{B}_{17}\text{W}_2$	800°C	1100	10.79
27				

plasma gun and sprayed as a coating onto metal substrates with good adhesion and with absence of cracking. Other methods for forming a coating of DNC steel include axial feed plasma spray, conventional plasma spray, high velocity oxy-fuel spray, and a detonation gun.

When DNC steel is sprayed onto metallic substrates it can readily form a metallic glass structure. If consecutive layers are continuously sprayed onto a bulk substrate (thickness greater than 0.1 inches) metallic glasses can be formed. This may be the most inexpensive and easiest way to form bulk metallic glass coatings or even bulk glass monolithic parts.

DNC steels can be rapidly solidified into an amorphous glass precursor and then the rapidly solidified powders can be consolidated into a useful form. Accordingly, the cost of technology of the present invention can involve three items: the alloy cost, the powder production cost, and the consolidation cost. All three items can be estimated. To produce rapidly solidified powder, centrifugal atomization may be the best method, and even at relatively low production rates. If it is feasible to produce DNC steel powder by water atomization, processing cost to produce the powder could drop to a few pennies per pound. The powder consolidation costs will vary depending on the specific application and the thickness of the coating. Coatings from 5 micrometers to 2,500 micrometers in thickness can be readily deposited using conventional commercially available thermal deposition methods, such as plasma spraying or high velocity oxy-fuel spraying. The DNC steel's cost can compare favorably to other hard materials such as, for example, diamond and cubic BN. DNC steel coating may also be a direct competing technology to

1 replace tungsten carbide cemented carbide coatings, since the DNC steel exhibits higher
2 hardness and greater tensile ductility.

3 Although the invention is described herein for coating steel alloy compositions of
4 the present invention on metallic substrates, it is to be understood that the alloys of the
5 present invention can also be coated on non-metallic substrates, such as, for example,
6 ceramics, to provide a hard and/or lubricating surface over the non-metallic substrates.

7 In compliance with the statute, the invention has been described in language more
8 or less specific as to structural and methodical features. It is to be understood, however,
9 that the invention is not limited to the specific features shown and described, since the
10 means herein disclosed comprise preferred forms of putting the invention into effect. The
11 invention is, therefore, claimed in any of its forms or modifications within the proper
12 scope of the appended claims appropriately interpreted in accordance with the doctrine of
13 equivalents.